Below is the final report for the aforementioned grant sponsored by your office.

(1) Tasks Completed and Results

a. Under the support of the NASA grant, we have developed a new geometric-optics model (GOM2) for the calculation of the single-scattering and polarization properties for arbitrarily oriented hexagonal ice crystals. From comparisons with the results computed by the finite-difference time domain (FDTD) method, we show that the novel geometric-optics can be applied to the computation of the extinction cross section and single-scattering albedo for ice crystals with size parameters along the minimum dimension as small as ~6. Overall agreement has also been obtained for the phase function when size parameters along the minimum dimension are larger than ~20. We demonstrate that the present model converges to the conventional ray-tracing method for large size parameters and produces single-scattering results close to those computed by the FDTD method for size parameters along the minimum dimension smaller than ~20 (Yang and Liou 1996a). The FDTD method for the solution of light scattering by nonspherical particles has been developed for small ice crystals of hexagonal shapes, commonly occurring in cirrus clouds. In computing the scattered field in the far field and the absorption cross section, we have applied a new efficient algorithm involving the integration of the electric field over the volume inside the scatterer on the basis of electromagnetic principles. The applicability and the accuracy of the FDTD technique are validated by comparison with Lorenz-Mie scattering results for a number of size parameters and wavelengths. We demonstrate that neither the conventional geometric optics method nor the Lorenz-Mie theory can be used to approximate the scattering, absorption, and polarization features for hexagonal ice crystals with size parameters from approximately 5 to 20 (Yang and Liou 1996b). By unification of the GOM2 and FDTD methods for size parameters larger and smaller than about 20, we now have the theoretical and numerical tool to compute the single-scattering and polarization properties of ice crystals for all sizes and shapes that can be numerically defined, such as solid and hollow columns, double and single plates, bullet rosettes, dendrites, aggregates, and ice particles with rough surfaces. This is referred to as the unified theory for light scattering by ice crystals.

b. On the satellite remote sensing algorithm development and validation, we have developed a numerical scheme to identify multimultilayer cirrus cloud systems using AVHRR data. It is based on the physical properties of the AVHRR channels 1-2 reflectance ratios, the brightness temperature differences between channels 4 and 5, and the channel 4 brightness temperatures. In this scheme, clear pixels are first separated from cloudy pixels, which are then classified into three types: cirrus, cirrus/low cloud, and low clouds. We have applied this scheme to the satellite data collected over the FIRE II IFO area during nine overpasses within seven observation dates. Determination of the threshold values used in the detection scheme are based on statistical analyses of these satellite data. Validation of the detection results has been performed against the cloudy conditions inferred from the collocated and coincident ground-based lidar and radar images, balloonborne replicator data, and NCAR CLASS humidity soundings on a case-by-case basis. In every case, the satellite detection results are consistent with the cloudy conditions inferred from these independent and complementary measurements. The present scheme is well suited for the detection of midlatitude multilayer cirrus cloud systems and tropical anvils.

(2) Publications Acknowledging the Support of NASA Grant 1-1966 (and 1-1719, University of Utah)

Liou, K.N., 1996: Issues related to parameterization of the radiative properties of ice clouds in GCMs. *World Climate Research Programme Research, WCRP-90, WMO/TD No. 713*, pp.233-247.

Ou, S.C., K.N. Liou, and B. Baum, 1996: Detection of multilayer cirrus cloud systems using AVHRR data: Verification based on FIRE-II-IFO composite measurements. *J. Appl. Meteor.*, *35*, 178-191.

Yang, P., and K.N. Liou, 1996a: A geometric-optics-integral-equation method for light scattering by nonspherical ice crystals. *Appl. Opt. 35*, 6568-6584.

Yang, P., and K.N. Liou, 1996b: Finite-difference time domain method for light scattering by small ice crystals in three-dimensional space. *J. Opt. Soc. Am. A., 13*, 2072-2085.

Yang, P., and K.N. Liou, 1997: Light scattering by hexagonal ice crystals: solution by a ray-by-ray integration algorithm. *J. Opt. Soc. Am. A., 14*, 2278-2289.

Yang, P., K.N. Liou, and W.P. Arnott, 1997: Extinction efficiency and single-scattering albedo for laboratory and natural cirrus clouds. *J. Geophys. Res. 102*, 21,825-21,835.

Fu, Q., K.N. Liou, M. Cribb, T.P. Charlock, and A. Grossman, 1997: On multiple scattering in thermal infrared radiative transfer. *J. Atmos. Sci., 54*, 2799-2812.

Ou, S.C., K.N. Liou, and T. Caudill, 1998: Remote sounding of multilayer cirrus cloud systems using AVHRR data collected during FIRE-II-IFO. *J. Appl. Meteor., 37,* 241-254.

Yang. P., and K.N. Liou, 1998a: An efficient algorithm for truncating spatial domain in modeling light scattering by finite-difference technique. *J. Compt. Phys., 140*, 346-369.

Yang, P., and K.N. Liou, 1998b: Single-scattering properties of complex ice crystals interrestrial atmosphere. *Contr. Atmos. Phys. 71*, 223-248.

Ou, S.C., K.N. Liou, M.D. King, and S.C. Tsay, 1999: Remote sensing of cirrus cloud parameters based on a 0.63-3.7 um radiance correlation technique applied to AVHRR data. *Geophys. Res. Lett., 26*, 2437-2440.

Yang, P., K.N. Liou, K. Wyser, and D. Mitchell, 2000: Parameterization of the scattering and absorption properties of individual ice crystals. *J. Geophys. Res. 105*, 4699-4718.

Rolland, P., K.N. Liou, M.D. King, S.C. Tsay, and G.M. McFarquhar, 2000: Remote sensing of optical and microphysical properties of cirrus clouds using MODIS channels: methodology and sensitivity to assumptions. *J. Geophys. Res., 105*, 11,721-11,738.

3. Graduate Students who Participated: P. Yang: P. Rolland

I hope that you find the aforementioned report appropriate and acceptable. Thank you for your support of my research program at UCLA.